Imbalance Identification and Compensation for an Airborne Telescope

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Abstract

Airborne telescopes are typically supported by spherical bearings to prevent angular motions of the aircraft from affecting telescope pointing accuracy. Mass balancing of the telescope about the center of rotation is necessary to minimize the motor torque requirements. A static-balancing procedure that uses peg-mounted and moving counterweights to make the telescope center of mass coincident with the center of rotation is presented. Force-transducer measurements of the imbalance torque were used to identify the mass imbalance. A least-squares-directed search algorithm was developed to optimize placement of peg-mounted and moving counterweights for coarse and fine balancing. When implemented on a ~100 kg laboratory prototype, the procedure achieved balancing to within a mass-moment error of 0.005 kg-m in less than 5 minutes. This is more accurate and up to 50 times faster than had been accomplished using previous methods. Two key developments for the achievement of these results were (1) imbalance identification using force transducers with both high accuracy near zero and high load capabilities and (2) an optimization method to place the discrete counterweights.

1. Introduction

Airborne telescopes are used for conducting astronomical research at high altitudes to reduce the effects of atmospheric distortion and attenuation. Airborne telescopes were first used at NASA Ames Research Center in 1965, when Gerard Kuiper used the NASA Convair 990 for near-infrared airborne astronomy. The Kuiper Airborne Observatory (KAO), a modified C-141A shown in Figure 1, with a 0.9 m-aperture Cassegrain reflecting telescope, began operations in 1974 and continued until 1995. The opening for the telescope is located forward of the wing. The Stratospheric Observatory For Infrared Astronomy (SOFIA) [1], a converted Boeing 747 shown in Figure 2, with a 2.5 m-aperture optical/infrared/sub-millimeter telescope, is scheduled to begin operations in 2001.

Figure 1: Kuiper Airborne Observatory (modified C-141A) [2]

Figure 2: SOFIA aircraft (modified Boeing 747), telescope [2]

To maintain pointing accuracy in the presence of aircraft vibrations and angular motions, spherical bearings are used to support both the KAO (air bearing) and (planned) SOFIA (hydraulic bearing) telescopes. The near-frictionless bearing isolates the angular orientation of the telescope from angular motions of the aircraft. The KAO telescope is shown in Figure 3. The telescope cavity is on the right and is exposed to the outside air. The spherical air bearing can be seen in the middle, with the structure for mounting science instruments (to collect the focused optical and infrared radiation) and balancing counterweights (CWs) on the left.

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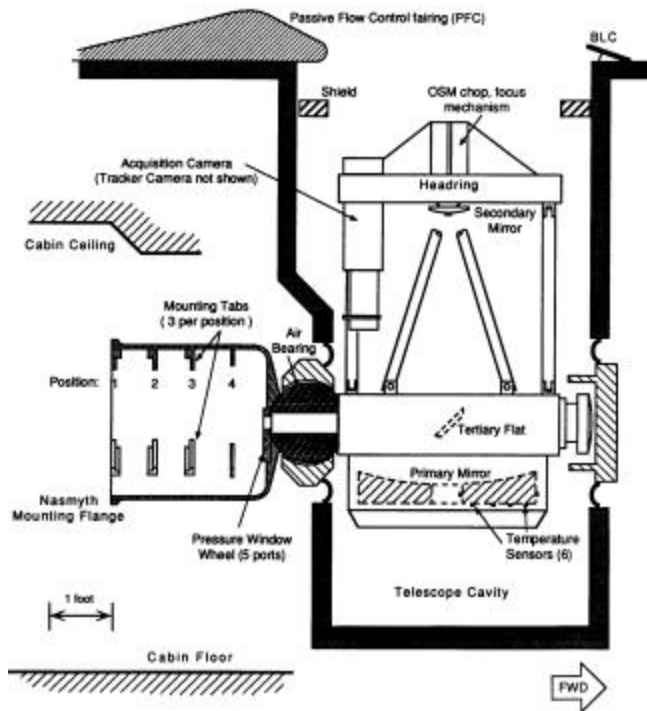
Figure 3: Cassegrain telescope on KAO [3]

If the telescope's center of mass (CM) is not perfectly coincident with the spherical bearing's center of rotation (CR), mass-imbalance torques will result. The goal of pre-flight balancing is to align the CM and CR to minimize the imbalance torques caused by the remaining misalignment. In addition to these imbalance torques, cables, aerodynamic forces, and other effects produce disturbances in flight. These effects are not addressed by the pre-flight balancing procedure presented here. It generally is not possible or practical to perfectly balance the telescope. Pre-flight balancing to an accuracy better than the level of these extraneous torques may not be necessary. The goal of pre-flight balancing is to reduce these residual torques to a level low enough that can be compensated for during flight by the telescope-pointing-control torque motors.

Pre-flight balancing (placing fixed CWs and positioning moving CWs to null the imbalance torques) is performed after the telescope has been outfitted with the required science instruments and is often one of the last steps before flight. Considering the value of time for an airborne observatory, the primary goal of this research has been to automate this procedure, with the expected benefit being time savings in pre-flight preparation.

The approach taken here is to
1) Use measurements of the imbalance torques to make a least-squares-based identification of the imbalance mass-moment about each axis.
2) Use an iterative search directed by least-squares fitting to determine the optimal locations of the discrete-sized, fixed-position counterweights.

3) Move the moving CWs to zero the remaining (quantization) error.

2. Existing balancing procedure

This technology was developed to support SOFIA, but as that design is not yet finalized, the KAO telescope was used as benchmark for these developments. This ensured that all practical issues were addressed.

The SOFIA telescope is approximately 3 times as large as the KAO telescope, which is twice as large as the laboratory model. The balancing procedure was developed so as to be applicable to all three telescopes.

The 0.9 m-aperture KAO telescope assembly is shown in Figure 3. Ten threaded rods protrude from the mounting plate on the aft end of the telescope in a pattern similar to that in Figures 5 and 6. They are used for mounting science instruments and attaching fixed, peg-mounted CWs with the following available sizes: 0.45, 2.27, 3.18, and 5.90 kg.

The current practice on the KAO is for two operators to add, move, or remove CWs on a trial and error basis. The telescope is driven to a certain elevation angle, held in place, and then its trajectory is observed when it is released briefly. Based on extensive experience, the operators are able to eventually arrive at a weight distribution that will balance the telescope. This procedure takes up to 4 hours. Once the final arrangement of discrete-valued peg-mounted CWs has been determined, a small error may still exist. Adjusting the moving CWs on all three axes can eliminate this quantization error. These are masses that move on lead screws that can be turned manually or driven by a motor as part of the KAO telescope's automatic control system.

3. Laboratory Model

To develop the automated balancing procedure, a ½-scale laboratory model of the KAO telescope was built. Figure 4 shows a side view taken before the balancing equipment was added. The model is constructed of Aluminum and has a total mass of approximately 100 kg. The model currently has a mechanical spherical bearing, peg-mounted CWs, and motor-controlled moving CWs. Unlike the KAO or SOFIA telescopes, it has no optical components or torque motors for pointing control.

As air bearings are expensive and consume air or electricity, a mechanical spherical bearing was used. A single 75 mm-diameter steel ball is supported by about 30 smaller ball bearings, riding in a spherical cup. This results in an excellent mechanical simulation of an air bearing: with a 1000N load, torques due to bearing friction and imperfections are below 0.05 N-m.
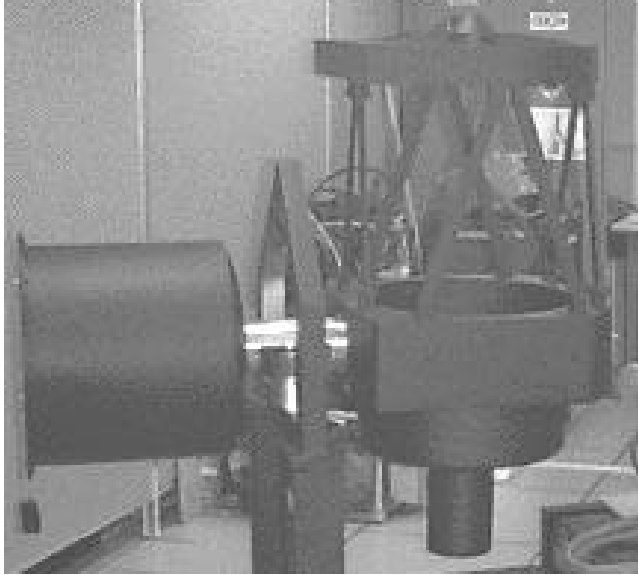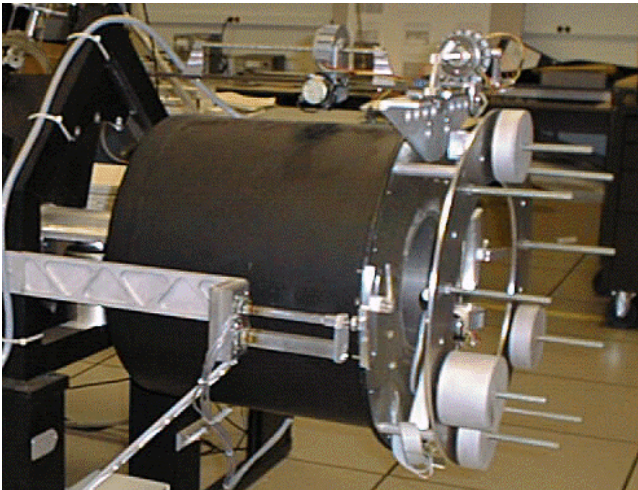
Figure 4: Scale model of KAO used for experiments

Figure 5: Lab model with pegs, compound force transducers, moving counterweights installed

The mounting plate was designed to be similar to that of the KAO telescope. Nine weight-mounting pegs are used in an equally spaced circular pattern, as shown in Figures 5 and 6. FT attachment points are on both sides of the mounting plate. One of the two FTs is shown in Figure 7, and its design is shown in Figure 8. The two horizontal moving CWs are on top of the telescope. The vertical moving CW was installed after the photograph was taken.

Figure 6 was taken from the graphical user interface (GUI) for the software package developed as part of this research. In this case, force measurements have been made and the imbalance location identified. The cross hairs indicate the CR. The large outer circle represents the outer edge of the mounting plate. The open circle near 4 o'clock indicates the magnitude (arbitrarily assumed to be

5.76 kg to allow plotting of the mass-moment) and direction of the identified mass-moment imbalance. The area of this circle is proportional to the mass of the imbalance.
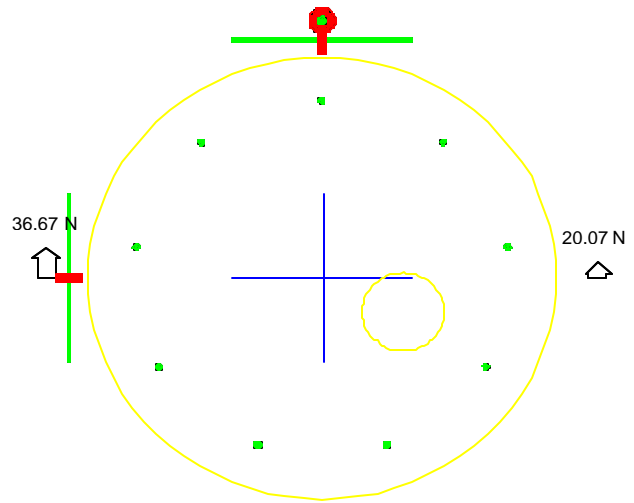

Figure 6: Graphical user interface, CW-peg layout

The upward arrows on the left and right indicate the predicted forces at the force transducer (FT) locations, with the telescope at the midpoint of its range of motion in elevation. The lengths of the force arrows are proportional to the force magnitude, and the base locations of the arrows indicate the actual geometric location of the force measurement points. Since the imbalance is on the -x side of the CR (into the paper), there is an upward force on each FT. Since the imbalance is on the right side of the CR, there is a net clockwise torque, indicated by the left force being higher than that on the right.

The two thin rectangles represent the lead screws for moving CWs on the y (horizontal) and z (vertical axes). The moving-CW masses are also shown, centered on the leadscrews. The circle above the y-axis leadscrew is an end view of the x-axis moving CW. This is what the system looks like before adding CWs or moving the moving CWs. The results after balancing with this initial configuration will be discussed further in Section 5 and shown in Figures 9 and 10.

Since the imbalance identification and subsequent weight placement is derived from the imbalance measurements, development of an accurate force measurement system was important. Measuring force due to imbalance at two points on the telescope and with the telescope at two different telescope-elevation angles (a total of four measurements) is sufficient to identify the xyz coordinates of the imbalance mass-moment. Measurement at different elevation angles is required to identify the vertical-axis component of the imbalance vector.

The requirements of the force-transducer system were determined so the system would work on the KAO telescope. Requirements are summarized as follows:

1) Measure forces up to 1000 N (225 pounds)
2) Measure forces near 0 N with high accuracy ($\ll$ 0.1 N if possible)
3) Take readings with the telescope at two or more elevation angles quickly and repeatably
4) Attach and detach quickly from the telescope
5) Measure forces on the laboratory model or KAO telescope, and also have a basic design that could be scaled up for use on the SOFIA telescope

Meeting requirements (1) and (2) simultaneously represents an accuracy of 0.01% of full-scale output (FSO) - a difficult requirement to meet. This problem was addressed by taking advantage of the fact that this high level of accuracy is only really needed near zero force. A compound FT with two cantilevered beams outfitted with foil strain gauges was designed and constructed, as shown in Figures 7 and 8.
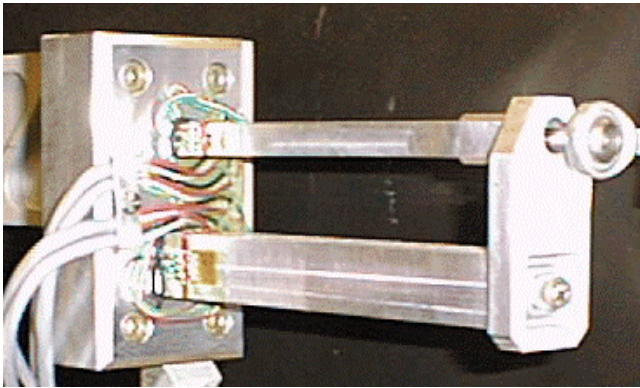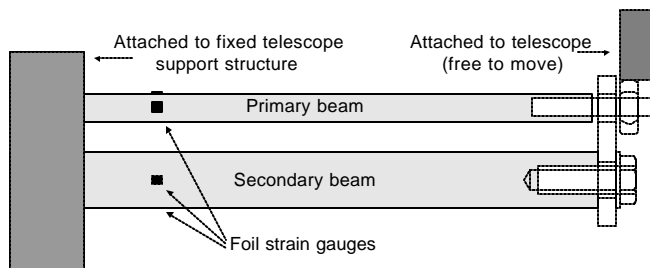

Figure 7: Compound force transducer

Figure 8: Compound force transducer design

The primary (smaller) beam measures loads up to 20 N with an accuracy near zero of about ±0.02 N. For forces above 20 N, the primary beam contacts a small plate attached to the secondary (larger) beam. As the load increases from 20 N to 1000 N, the secondary beam takes more of the load. At a total load of 1000 N, the primary beam supports 40 N and the secondary beam 960 N. This compound FT meets requirements (1) and (2). The overall design of the FT and attachment system met each of the requirements listed above.

4. Balancing Procedure

0) Preparation: calibrate FTs, including compensation for cross-coupling of horizontal forces; center moving CWs to maximize range of motion; note sizes and locations of any fixed CWs that may be attached; note any pegs that cannot be used because they are taken by a science instrument; measure locations of FT attachment points and peg locations (fixed values).

1) Take vertical force measurements with FTs at two attachment points, and with the telescope at two (or more) different elevation angles. This is a total of four (or more) numbers, required to identify the imbalance in three dimensions.

2) Find the telescope's imbalance mass properties using a least-squares identification [4]. The imbalance is considered as an "imbalance mass moment." For example, 1 kg at 1 mm from the CR will produce the same effect as 1 g at 1 m, since these both have the same mass moment (MM) of 0.001 kg-m. A least-squares fit to the force measurement data produces the total MM, including telescope and CWs, if any. If CWs were in place, their contribution to the total MM is calculated and subtracted. The thickness of the weights is accounted for in calculating the effect of CWs. For example, the second weight on a peg contributes a different amount to the MM than the first, since the center of mass is further from the CR. The result is an estimate of the imbalance MM in all three dimensions.

3) Use a search algorithm to find the optimal set of weight locations that will produce a CW MM counteracting the imbalance MM. This could be done using a least squares fit, but must be constrained in three ways: (1) to prevent assignment of negative-mass weights; (2) to prevent assignment of weights exceeding the maximum allowable per peg; and (3) to accommodate the discrete CW sizes available. An additional complication is that the thickness of the counterweights must be accounted for in calculating their contribution to the total MM. On the laboratory model, available CW masses are 0.11, 0.33, 0.55, and 1.44 kg.

As a test of optimality after weight locations have been assigned, the remaining imbalance is compared to perturbations of the optimal solution which include: adding or subtracting the smallest weight from each peg (where possible), and moving the smallest weight on each peg to each of the other pegs (where possible). The search algorithm has not been proven optimal; however, these final-check perturbations have never found a better solution.

The weight-placement algorithm is not dependent on any symmetry in the layout of available pegs. This was an

operational consideration, since some mounting pegs may be used to attach science instrument hardware.

4) Manually place the peg-mounted CWs on pegs as indicated by the previous step.

5) Repeat steps 2 and 3 (different only in that locations of CWs are not entered – in this case, the total mass-moment of the telescope, including CWs is identified). Although not required, this step will improve balancing accuracy, since the FT accuracy is higher near zero and the CW masses, thicknesses, and peg locations are not known exactly.

6) Knowing the geometric and mass properties of the moving CWs, calculate the relative movement needed to counteract the remaining imbalance.

7) Move the moving CWs as needed. Since the wires that drive the moving CW leadscrews would produce a relatively significant disturbance torque, they remain disconnected throughout the procedure except during this step.

8) The telescope should now be balanced. It can be detached from the FTs and should remain motionless when positioned at any angle. When set in motion, it should continue at constant velocity until hitting a travel limit. The primary limiting factors in achieving this state of perfect balance are bearing friction / imperfections and FT accuracy.

5. Results from Balancing on the Laboratory Model

The procedure described in Section 4 was implemented and controlled by a MATLAB program that provided the graphical user interface (GUI), directed the manual portions of the balancing procedure, identified the imbalance, computed the CW locations, and controlled the moving CWs [5]. The total procedure can be carried out in less than 5 minutes.

Figures 9 and 10 show the final CW configuration, as presented to the operator. This case represents the same imbalance that was shown before balancing in Figure 6. A visual check confirms that the CW masses counteract the imbalance mass: the mass-moment of the counterweights can be seen to cancel that of the imbalance (about horizontal and vertical axes shown here). Manually finding this CW configuration by observing the telescope trajectory after release is extremely difficult.

The moving CW positions are shown graphically and labeled in mm. The peg-mounted CW locations are indicated in 3 ways: (1) the pegs with CWs have shaded circles, with the area of the circle proportional to the total mass of CWs on that peg. (2) The actual number of each type of CW is indicated next to each peg. For example, the peg at approximately 9 o'clock indicates CWs of "2 0 0 0" -- meaning two of the largest CWs and no others. (3) The total mass in kg is also indicated on the radially inward side of each peg. To avoid clutter, empty pegs are not labeled.

The side view, shown in Figure 10 is useful for visualizing the original location of the imbalance mass, the counterbalancing mass added, and the fact that one cancels the other, reflecting exactly on both axes through the CR. As in Figure 9, the area of the peg-mounted counterweights is proportional to the mass.

The procedure produced consistent results from one run to the next. The results for a typical run will be discussed. If the weights were placed as indicated, and one final measurement taken with the telescope at an elevation angle of 0 degrees, the FTs would each read 0 (perfect balance) ±0.02 N. The limiting factors on balancing accuracy are the repeatability of the FTs near zero and the friction of the spherical bearing, both of which affect the force measurements.
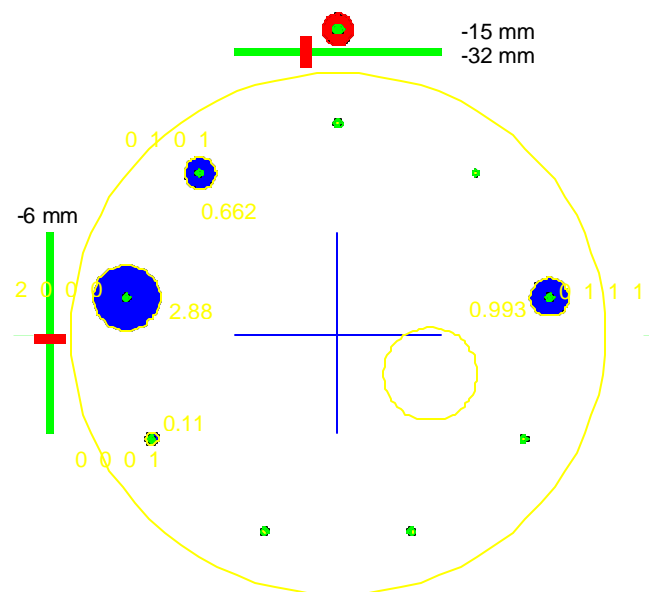

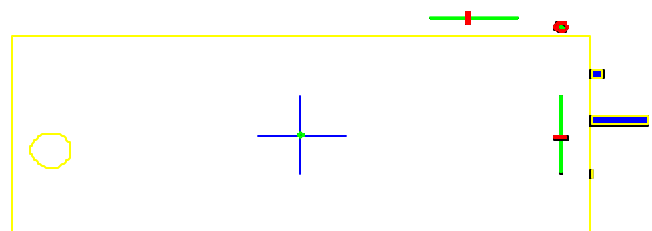Figure 9: Example of GUI final output, front view

Figure 10: Example of GUI final output, side view

The real test came when the FTs were disconnected from the telescope. If the telescope could be *perfectly* balanced and no disturbance torques were present, it could be placed in any angular

orientation and remain motionless or move with constant angular velocity when released or disturbed.

When a near-perfect state of balance was achieved, it became possible to detect the minor flaws in the mechanical spherical bearing. For example, when released with a velocity of about one degree per second, the trajectory was not straight. It appeared that the effect of the individual ball bearings supporting the main ball bearing would cause the telescope to move in an irregular pattern. To quantitatively validate the accuracy of balance, a 10 g weight could be placed on the telescope at a radius of approximately 0.5 m. The telescope would then start to fall in the direction of the mass, indicating that balance was good to better than 0.005 kg-m.

This degree of accuracy has little practical value for airborne-telescope balancing, since other torques due to aerodynamics, cables, etc. will be much larger than the residual error. However, achieving balance limited by FT and bearing effects validates the balancing procedure and provides a solid foundation for future research on nonlinear and time-varying effects.

In summary, the balancing was quick, repeatable, and accurate to within a few grams when balancing a 100 kg telescope. The accuracy was limited by friction in the spherical bearing and the repeatability of the FTs. The experimental results validate the overall approach.

6. Conclusions and Future Research

An automated procedure for pre-flight balancing of an airborne telescope can achieve balancing to an accuracy limited by the ability to measure imbalance torques. A least-squares fit to imbalance torque measurements is a viable approach for imbalance identification. A least-squares-directed search can successfully optimize placement of counterweights for this application. This procedure can be carried out in minutes, in contrast to the hours usually required for manual balancing. In tests on a 100 kg laboratory model of an airborne telescope, balancing took less than 5 minutes and resulted in residual imbalance torques of less than 0.05 N-m.

The compound-force-transducer design, imbalance identification, and weight placement algorithms developed here may apply to general spherical bearing balancing applications, determining mass properties of systems, and solving similar optimization problems. The technology developed to address the balancing problem presented here will serve as a foundation for further research to support pre- and in-flight balancing of the SOFIA telescope, including:

- Methods to compensate for torques due to cabling and aerodynamic forces
- A system to optimize balancing during the course of an experiment as the CM changes due to cryogenic boil off

- Use of neural-network methods to adaptively identify and compensate for nonlinear imbalance effects.[2]

References:

[1] Erickson, E. F. *SOFIA: The Next Generation Airborne Observatory.* Space Science Reviews, 74, 91-100, 1995.
[2] NASA Photo.
[3] NASA Drawing.
[4] Franklin, G. F. and Powell, J. D. *Digital Control of Dynamic Systems.* Addison-Wesley Publishing, New York, 1990.
[5] MATLAB is a registered trademark of The MathWorks, Inc., 24 Prime Park Way, Natick, MA 01760, 508-647-7000.

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[2] Development of neural-network-based balancing methods is the primary goal of this research at the NASA Ames Research Center Neuroengineering laboratory. The approach of the authors for developing an intelligent balancing system has been to use neural and linear-systems technologies where appropriate. Since mass-imbalance is a highly linear effect, neural networks were not used here. Neural networks are expected to be valuable in providing for identification and compensation of nonlinear effects such as cabling and aerodynamics, work that will build upon the research presented here.